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Date: May 16, 2007

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Dear Dr. Arias,

Attached is the report of our most recent formal evaluation of NIST-F1, a cesium fountain primary frequency standard. The report period is for the 15 day interval from MJD 54219 to 54234. However, the fountain was operated in a virtually continuous fashion over a shorter evaluation interval from MJD 54219.00 to 54231.67 Details of the standard's design, construction, and performance are presented in references 1 - 8 listed on page 8. A detailed summary of the present evaluation is included in this report. The evaluation results using the BIPM format are given on pages 2 and 7.

This is the second half of the April/May operation of NIST-F1. There are no significant changes in NIST-F1 since the last report.

Thomas E. Parker
Leader, Atomic Frequency Standards Group

## SUMMARY

### May 2007 Evaluation of NIST-F1

The most recent evaluation of NIST-F1 is reported. The number

$$Y_{(NISTF1\text{-}maser)} = -301.29 \times 10^{-15}$$

is the average fractional frequency difference between NIST-F1 and the hydrogen maser ST0005, (clock # 40205) over the 15 day report period MJD 54219 to 54234. The type A uncertainty of the fountain for this evaluation (statistical confidence on the frequency measurement including a component due to spin exchange, but not including dead time) is $0.41 \times 10^{-15}$ ($1\sigma$). The type B uncertainty from known biases (not including spin exchange) is $0.33 \times 10^{-15}$ ($1\sigma$). The combined uncertainty (type A and type B) is $0.53 \times 10^{-15}$ ($1\sigma$). The uncertainty becomes $0.56 \times 10^{-15}$ ($1\sigma$) when the contribution from dead time, $u_{link/lab}$, is included. A detailed description of the various biases and uncertainties is given in the following sections of this report.

RESULTS IN BIPM FORMAT

| | | |
|---|---|---|
| Report period | | MJD 54219 to 54234 |
| Maser frequency (ST0005), clock # 40205) | | $Y_{(NISTF1 - maser)} = -301.29 \times 10^{-15}$ |
| Statistical | $u_A$ | $0.41 \times 10^{-15}$ |
| Systematic | $u_B$ | $0.33 \times 10^{-15}$ |
| Link to clock | $u_{link/lab}$ (15 days) | $0.18 \times 10^{-15}$ |
| Link to TAI (estimated) | $u_{link/TAI}$ (15 days) | $0.61 \times 10^{-15}$ |
| Combined (estimated) | $u$ | $0.83 \times 10^{-15}$ |

## 1. DETAILS OF EVALUATION

An accuracy evaluation of NIST-F1 has been completed in which the frequency of a hydrogen maser was determined with respect to the primary frequency standard. The report period is 15 days, but the fountain was operated only over the 12.67 day evaluation interval of MJD 54219.00 to 54231.67. Of the 12.67 days intended for the measurement of the maser frequency, 12.49 days of data were collected (98.6% run time). The lost run time was from intentional interruptions to the fountain operation for routine maintenance. The percentage run time for the entire report period is 83.3%. A time line of the 15 day report period is shown in Table 1 below.

Table 1: Time Line

| MJD | Event |
|---|---|
| 54219.00 | Start report period |
| 54219.00 | Start fountain run, high density (40) |
| 54219.92 | End high density, |
| 54219.93 | Start low density (8) |
| 54231.67 | End low density, end fountain run |
| 54234.00 | End report period |

A factor of 5 in atom densities was covered in this evaluation and the frequency for zero density was obtained by a weighted linear least-mean-square fit [3]. The atom densities in laboratory units are shown in parentheses in Table 1. Other corrections are also made to the raw frequency data in order to compensate for known biases which are described below [2]. Units for all biases are fractional frequency $x10^{-15}$ and all uncertainties are 1 sigma.

### A. Quadratic Zeeman Bias

The quadratic Zeeman bias was determined by measuring the linear Zeeman splitting of the microwave spectrum. The magnetic field was monitored during the entire run. No significant changes were made to the Zeeman bias since the last run. The resulting bias and uncertainty are shown below.

| Bias | Type B Uncertainty |
|---|---|
| +180.90 | 0.013 |

B. Spin Exchange Bias

Measurements were made over a range of atom densities. A factor of 5 in atom density was covered and the frequency at zero density was obtained from the zero density intercept of a weighted linear least-mean-square fit of frequency versus atom density [3]. Thirteen data points (each nominally 24 hours) were used in the fit and a reduced chi squared of 1.82 was obtained. This corresponds to a Birge ratio of 1.35. With only 13 days of data this is a relatively short run and this Birge ratio does not have much statistical significance. Using the April data gives an additional 11 data points. Including this data gives a Birge ratio of 1.17 which is more statistically significant (the April data is only used to calculate the Birge ratio and is not used to calculate the spin exchange shift for this report). As in the February and April reports it was decided to increase the uncertainty attributed to the spin exchange bias by this Birge ratio [3]. By using a range of atom densities there is no fixed spin exchange bias, however the bias in fractional frequency from the lowest measured density to zero density was $-0.63\times10^{-15}$ with an uncertainty of $0.20\times10^{-15}$. These values are shown below for informational purposes only. They are not included in the total of the type B biases and uncertainties of Table 2 since they are already incorporated into the intercept and its uncertainty (type A uncertainty). Note that 92% of the fountain run time was at the lowest atom density.

| Bias | Type B Uncertainty |
|---|---|
| (-0.63) | (0.20) |

C. Blackbody Bias

The blackbody bias is calculated from the temperature of the drift region. The resulting bias and its uncertainty are shown below.

| Bias | Type B Uncertainty |
|---|---|
| -22.84 | 0.28 |

D. Microwave Amplitude Shift

No additional measurements on the microwave amplitude dependence were made so the uncertainty is unchanged. The observed bias is consistent with zero, but we have chosen to include it in the list of corrected biases.

| Bias | Type B Uncertainty |
|---|---|
| -0.05 | 0.15 |

E. Combined variable and fixed biases

There are additional biases that do not change under normal circumstances. The complete list of all biases (run dependent and fixed) and their corresponding uncertainties are shown in Table 2. This table is based on [2]. Only the first 4 biases are explicitly corrected for since the rest are all well under $1 \times 10^{-16}$. The maximum magnitudes of all uncorrected biases are indicated in blue. The spin exchange bias is not corrected in the same manner as the others since it is included in the intercept of the weighted least-mean-square fit of frequency versus atom density.

Table 2: Known Frequency Biases and Their Type B Uncertainty.
(Units are fractional frequency $\times 10^{-15}$)

| Physical Effect | Bias | Type B Uncertainty |
|---|---|---|
| Gravitational Red shift | +179.95 | 0.03 |
| Second-Order Zeeman | +180.90 | 0.013 |
| Blackbody | -22.84 | 0.28 |
| Microwave Amplitude Shift | -0.05 | 0.15 |
| Spin Exchange (low density) | (-0.63)* | (0.20)* |
| AC Zeeman (heaters) | 0.05 | 0.05 |
| Cavity Pulling | 0.02 | 0.02 |
| Rabi Pulling | $10^{-4}$ | $10^{-4}$ |
| Ramsey Pulling | $10^{-4}$ | $10^{-4}$ |
| Majorana Transitions | 0.02 | 0.02 |
| Fluorescence Light Shift | $10^{-5}$ | $10^{-5}$ |
| Cavity Phase (distributed) | 0.02 | 0.02 |
| Second-Order Doppler | 0.02 | 0.02 |
| DC Stark Effect | 0.02 | 0.02 |
| Background Gas Collisions | $10^{-3}$ | $10^{-3}$ |
| Bloch-Siegert | $10^{-4}$ | $10^{-4}$ |
| RF Spectral purity | $3 \times 10^{-3}$ | $3 \times 10^{-3}$ |
| Integrator offset | 0 | 0.01 |
| | Total Type B Standard Uncertainty | 0.33 |

*For information purposes only. Not used in total, see section 1-B for details

## 2. EVALUATION INTERVAL RESULTS (MJD 54219.00 to 54231.67)

When corrections for the biases of Table 2 are applied, the following result for the measurement of $Y_{(NISTF1\text{-}maser)}$ is obtained. Because the type A uncertainty includes the spin-exchange bias uncertainty, we include (in parentheses in the table below) the combined statistical uncertainty of all the data collected in this evaluation (as if there were no need for a linear fit). This is included only for its informational value. Units are fractional frequency $x10^{-15}$.

| Corrected Frequency | Type A Uncertainty - includes spin exchange | Total Type B Uncertainty - does not include spin exchange | Combined Uncertainty |
|---|---|---|---|
| -301.29 | 0.41<br>(0.25) | 0.33 | 0.53 |

## 3. INFLUENCE OF DEAD TIME

NIST-F1 was operated for a total of only 12.49 days during this 15 day report period so the dead time has an impact on the overall uncertainty. However, NIST has a well characterized ensemble of hydrogen masers so this impact can be quantified. The frequency stability and drift of the reference maser are well known. No drift correction was required because the frequency drift on this maser is very small and there was relative little dead time. However, the dead time contributes an additional type A uncertainty of $0.18x10^{-15}$. See references 10 - 13. A new procedure was used to handle distributed dead time [13]. This results in an improved estimate of the dead time uncertainty.

4. FINAL REPORT PERIOD RESULTS (without time transfer uncertainty)

Applying the correction resulting from dead time to the evaluation interval results yields the following 15 day final report period results.

| | |
|---|---|
| Report period | MJD 54219 to 54234 |
| Maser frequency (ST0005, clock # 40205) | $Y_{(NISTF1 - maser)} = -301.29 \times 10^{-15}$ |
| Type A uncertainty (not including dead time) | $0.41 \times 10^{-15}$ ($1\sigma$) |
| Type B uncertainty | $0.33 \times 10^{-15}$ ($1\sigma$) |
| Combined uncertainty (fountain only) | $0.53 \times 10^{-15}$ ($1\sigma$). |
| Type A uncertainty from dead time | $0.18 \times 10^{-15}$ ($1\sigma$) |
| Combined uncertainty with dead time | $0.56 \times 10^{-15}$ ($1\sigma$). |

5. FINAL RESULTS USING BIPM FORMAT (includes time transfer uncertainty)

| | | |
|---|---|---|
| Report period | | MJD 54219 to 54234 |
| Maser frequency (ST0005), clock # 40205) | | $Y_{(NISTF1 - maser)} = -301.29 \times 10^{-15}$ |
| Statistical | $u_A$ | $0.41 \times 10^{-15}$ |
| Systematic | $u_B$ | $0.33 \times 10^{-15}$ |
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| Combined (estimated) | u | $0.83 \times 10^{-15}$ |

## 6. REFERENCES


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## Appendix A

### Summary of accumulated changes in biases and uncertainties since the state of NIST-F1 discussed in references 2 and 3

(1) 30 day evaluation of June/July 2005 (MJD 53529-53559)
Modifications to the optical detection electronics and the low noise quartz oscillator improved the stability ($u_A$) of NIST-F1. More measurements with respect to microwave leakage reduced this uncertainty from $2x10^{-16}$ to $1.4x10^{-16}$.

(2) 40 day evaluation of September/October 2005 (MJD 53629-53669)
A magnetic field monitor was added to NIST-F1. No change was needed in the second order Zeeman bias uncertainty. Also, no other Type B uncertainties have been changed.

(3) 40 day evaluation of December 2005/January 2006 (MJD 53724-53764)
The fountain cycle time was shortened a bit and this resulted in a small improvement in short-term stability. Also the magnetic field uniformity was improved by shield degaussing and shimming, and this resulted in a small decrease in the Zeeman bias. There were no changes in the Type B uncertainties.

(4) 40 day evaluation of February/March 2006 (MJD 53784-53824)
No significant changes were made to NIST-F1 other than a slight increase in the average atom density. There were no changes in the Type B uncertainties.

(5) 30 day evaluation of October 2006 (MJD 54009-54039)
NIST-F1 was moved to a room with better environmental control and which is closer to the hydrogen masers and the time scale (shorter cables). The fountain was damaged in the move and as a result the microwave cavities, drift tube, and source region were replaced with nearly identical parts. All of the replaced parts are functionally the same as the originals. Because of the change in location and the repairs, the Zeeman and blackbody corrections are slightly larger, along with their uncertainties. The gravitational red shift is slightly smaller due primarily to the fact the fountain is now one floor lower than before, but there is no change in uncertainty. The bias and uncertainty for microwave leakage below the cavities are slightly larger.

(6) 20 day evaluation of February 2007 (MJD 54134-54154)
No significant changes were made to NIST-F1 for this evaluation, except that the magnetic field above the Ramsey cavity was increased by a factor of 2 in order to improve the field uniformity and decrease the possible effects of off resonant transitions. As an indirect result of these changes the atom cloud was slightly larger and probably colder. This resulted in a higher atom number at the lowest density used and consequently an improved short-term stability. Also additional microwave amplitude measurements were made to reduce the uncertainty on the microwave amplitude shift. This resulted in a slight decrease in the overall Type B uncertainty.

(7) 15 day evaluation of April 2007 (MJD 54204-54219)

No significant changes were made to NIST-F1 since the February 2007 evaluation.

(8) 15 day evaluation of May 2007 (MJD 54219-54234)
No changes were made to NIST-F1 since the April 2007 evaluation.